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Experimental and analytical studies of earth–air heat exchanger (EAHE) systems in India: A review

Trilok Singh Bisoniya*, Anil Kumar, Prashant Baredar

Department of Energy, Maulana Azad National Institute of Technology, Bhopal 462051, India

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ABSTRACT

This is the property of earth that at a depth of about 1.5 to 2 m, the temperature of ground remains almost constant throughout the year. This constant temperature is called earth's undisturbed temperature which remains higher than surface temperature of earth in winter season and vice versa in summer. For effective utilization of heat capacity of earth, the earth–air heat exchanger (EAHE) has to be designed. The EAHEs are considered as an effective passive heating/cooling medium for buildings. This is basically a series of metallic, plastic or concrete pipes buried underground at a particular depth through which the fresh atmospheric air flows and gets heated in winter and supplied to the building if at sufficiently high temperature and vice versa in summer. Till date many researchers have carried out a number of studies in designing, modeling and testing of EAHEs systems. This paper reviews on the experimental and analytical studies of EAHE systems around the world but the studies are mainly focused on EAHE systems at the Indian universities as of the end June, 2012.

Contents

1. Introduction

Given the importance of energy for the existence of our society as we know, it is imperative and urgent to find alternative sources to replace conventional fuel or at least mitigate its widespread consumption and consequent impact on the environment. The term alternative energy source does not imply only as an efficient option, but is synonymous of clean energy. This kind of energy is, at principle, inexhaustible and can be found and exploited equally well on the planet. In recent times, air conditioning is widely employed not only for industrial productions but also for the comfort of occupants. It can be achieved efficiently by vapour compression machines, but due to depletion of the ozone layer and global warming by chlorofluorocarbons (CFCs) and the need to reduce high grade energy consumption; numerous alternative techniques are being currently explored [1,2]. One such method is

Abbreviations: EAHE, earth–air heat exchanger; CFCs, chlorofluorocarbons; UAT, underground air tunnels; GSDCS, ground sink direct cooling system; CFD, computational fluid dynamics; SC, solar chimney; ANN, artificial neural network; GA, genetic algorithm; LCC, life cycle cost; COP, coefficient of performance; EPBT, energy payback time; EPF, electricity production factor.

* Corresponding author. Tel.: +91 9826880430.
E-mail address: tsbisoniya@gmail.com (T.S. Bisoniya).

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the earth–pipe–air heat exchanger systems. It uses underground soil as a heat source and air as the heat transfer medium for space heating in winter. Cold outdoor air is sent into the earth-to-air heat exchangers. When air flows in the earth–air–pipes, heat is transferred from the earth to the air. As a result, the air temperature at the outlet of the earth–air–pipes is much higher than that of the ambient. The outlet air from the earth–air–pipes can be directly used for space heating if its temperature is high enough. Alternatively, the outlet air may be heated further by associated air conditioning machines. Both of the above uses of earth–air–pipes can contribute to reduction in energy consumption.

Several researchers have described the earth-to-air heat exchangers (EAHE) coupled with buildings as an effective passive energy source for building space conditioning [3–5]. An earth-to-air heat exchanger system suitably meets heating and cooling energy loads of a building. Its performance is based upon the seasonally varying inlet temperature, and the tunnel-wall temperature which further depends on the ground temperature. The performance of an EAHE system depends upon the temperature and moisture distribution in the ground, as well as on the surface conditions [6]. Sodha et al. [7] have carried out rigorous experimental studies with a large earth-to-air heat exchanger system situated at Mathura, India. These models were based on several assumptions such as axially symmetric flow, constant pipe wall temperature, negligible humidity variations etc. Moreover, earth-to-air heat exchanger in these studies was analyzed independent of the effects of variations in ground temperature.

One of the important aspects in concern of EAHEs is categorization of the site in terms of geology availability. The knowledge of soil thermal and physical properties (thermal conductivity, density, diffusivity etc.), depth of bedrock, depth to water and the nature of soil is required. This information guides the designer in the selection of the type of EAHE system to be used and in the design of the system [8–16]. Two major types exist: 'open-loop' (Fig. 1) (i.e., drawing outside air through the pipes to ventilate the house) or 'closed-loop' (Fig. 2) (i.e., re-circulating the air from the building through the earth tubes). The second kind seems to have fallen out of favour, probably because it is insufficient to provide heating to the building by itself, and because it does not help meet the building's fresh air requirements.

The EAHE systems gained some popularity about three decades before but they were not used commonly by people either because of poor performance or because of certain disadvantages related to them like higher initial cost, decrease in air quality with increase in time of use, growth of fatal micro-organisms, transfer of fan noise through pipes to living space etc. The present requirement of use of renewable and sustainable energy technologies has again generated interest of researchers and scientists in the concept of EAHEs. Ozgener [17] presented a very insightful review on experimental and analytical analysis of earth to air heat exchanger (EAHE) systems in Turkey which motivated authors and provided guidelines to write this paper. The aim of this paper is to review the current state of the art regarding earth–air heat exchanger systems, using a literature search in scientific journals and conferences.

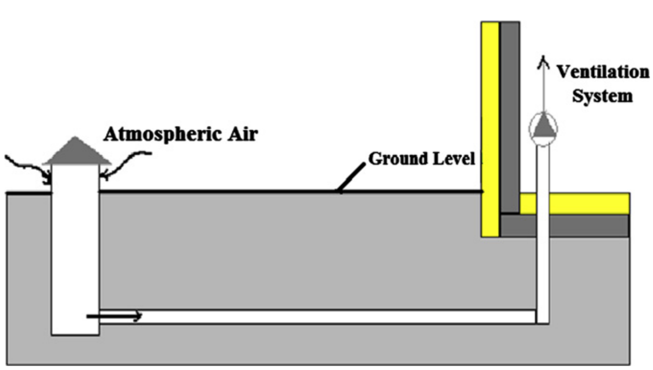


Fig. 1. Earth–air heat exchanger (open loop mode).

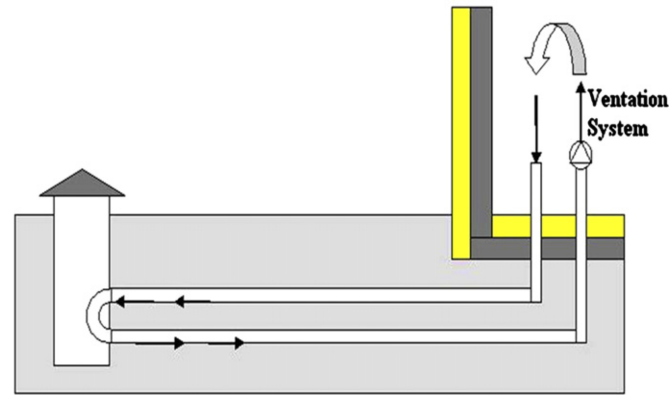


Fig. 2. Earth–air heat exchanger (closed loop mode).

The structure of the paper is as follows: The first section includes the introductory part; Section 2 describes a brief scenario of EAHE systems in the world, Experimental and analytical studies of EAHE systems around the world are investigated in the third section; Section 4 includes studies conducted on EAHE systems at the Indian universities, and the last section concludes.

2. A brief scenario of EAHE systems in the world

A ground-coupled heat exchanger is an underground heat exchanger that can capture heat from and/or dissipate heat to the ground. They use the earth's near constant subterranean temperature to warm or cool air or other fluids for residential, agricultural or industrial uses. If air from buildings is blown through the heat exchanger for heat recovery ventilation, they are called earth tubes (also known as earth cooling tubes or earth warming tubes) in Europe or earth–air heat exchangers (EAHE or EAHX) in North America. Earth tubes are often a viable and economical alternative or supplement to conventional central heating or air conditioning systems since there are no compressors, chemicals or burners and only blowers are required to move the air. These are used for either partial or full cooling and/or heating of facility ventilation air.

The idea of using earth as a heat sink was known in ancient times. In about 3000 B.C., Iranian architects used wind towers and underground air tunnels for passive cooling [18,19]. Earth–air heat exchangers have been used in agricultural facilities (animal buildings) and horticultural facilities (greenhouses) in the United States over the past several decades and have been used in conjunction with solar chimneys in hot arid areas for thousands of years, probably beginning in the Persian Empire. Underground air tunnel (UAT) systems, nowadays also known as earth to air heat exchangers (EAHEs), have been in use for years in developed countries due to their higher energy utilization efficiencies compared to the conventional heating and cooling systems. Implementation of these systems in Austria, Denmark, Germany, and India has become fairly common since the mid-1990s, and is slowly being adopted in North America.

Earth–air heat exchangers are one of the fastest growing applications of renewable energy in the world, with an annual increase in the number of installations with 10% in about 30 countries over the last 10 years [20]. With the exception of Sweden and Switzerland, the market penetration is still modest

throughout Europe [21] but is likely to grow with further improvements in the technology and the increasing need for energy savings.

From the middle of the 20th century, a number of investigators have studied the cooling potential of buried pipes [19]. Since that time, a number of experimental and analytical studies of this technique have appeared in the literature [26–34,50–54]. Till 2001, about 1000 passive house units have been built in Germany and this amount sensibly doubles every year [22]. In Europe, already more than 5000 passive house units have been successfully built and completed [23].

3. Experimental and analytical studies of EAHE systems around the world

The main advantages of EAHE system are its simplicity, high cooling and pre-heating potential, low operational and maintenance costs, saving of fossil fuels and related emissions [24]. Pre-heated fresh air supports a heat recovery system and reduces the space heating demand in winter. In summer, in combination with a good thermal design of the building, the EAHE can eliminate the need for active mechanical cooling and air-conditioning units in buildings, which will result in a major reduction in electricity consumption of a building if the EAHE is designed well. EAHEs are hence a passive cooling option in moderate climates.

The energy performance of EAHEs is described by the thermal interaction of heat conduction in the soil taking moisture in consideration, heat transport by flowing and ground water, heat transmission from the pipe to the air and changes in the air temperature and humidity. Different parametric and numerical models for EAHEs have been published in the last two decades. Simulation models can be classified as models with an analytical or a numerical solution of the ground temperature field, and mixed models. Furthermore, mathematical or numerical optimization simply applies to one specified structure of the system whereas, often, structural modifications would be able to improve the cost effectiveness of the plant. Nevertheless, is not always possible or practical to develop a mathematical model for every promising design configuration of a system [25].

In the literature several calculation models for ground coupled heat exchangers are found. Tzaferis et al. studied eight models [26]. The compliance with measurements done by Tzaferis et al. is quite good. This shows that a steady-state one-dimensional model may characterize the behavior of the earth–air heat exchangers Mihalakakou et al. [27], Bojic et al. [28], Gauthier et al. [29], and Hollmuller et al. [30] have reported on more complete and dynamic models for earth–air heat exchangers. Wu et al. [31] developed a transient and implicit model based on numerical heat transfer and computational fluid dynamics (CFD) and then implemented it on the CFD platform, PHOENICS, to evaluate the effects of the operating parameters (i.e., the pipe length, radius, depth and air flow rate) on thermal performance and cooling capacity of earth–air–pipe systems. Bhutta et al. [32] presented a very useful review on applications of CFD in the field of heat exchangers. It is concluded that CFD is an effective tool for predicting the behavior and performance of a wide variety of heat exchangers.

Sehli et al. [33] proposed a one-dimensional numerical model to check the performance of EAHEs installed at different depths. It was concluded that EAHE systems alone are not sufficient to create thermal comfort, but can be used to reduce the energy demand in buildings in South Algeria, if used in combination with conventional air-conditioning systems. Cucumo et al. [34] proposed a one-dimensional transient analytical model to estimate the performance of earth-to-air heat exchangers, installed at different depths, used for building cooling/heating. Badescu [35] developed a simple and accurate ground heat exchanger model. It was based on a numerical transient bi-dimensional approach that allows computing of the ground temperature at the surface and at various depths. The heating and cooling potential of the system under real climatic conditions was investigated. The energy delivered by the ground heat exchanger depends significantly on different design parameters like pipe's depth, diameter and material.

Mihalakakou et al. [36], Lee and Strand [37] carried out a parametric analysis to investigate the effect of pipe radius, pipe length, air flow rate and pipe depth on the overall performance of the earth tube under various conditions during cooling season. Pipe length and pipe depth turned out to affect the overall cooling rate of the earth tube, while pipe radius and air flow rate mainly affect earth tube inlet temperature. Kabashnikov et al. [38] developed a mathematical model representing the temperature in the form of the Fourier integral for calculating the temperature of the soil and air in a soil heat exchanger for ventilation systems. The performance behavior of heat exchanger was studied with respect to change in length and diameter of tubes, spacing between tubes, air flow rate and depth of burial. The method developed does not need complicated calculations and can be referred for design considerations. Tittelein et al. [39] realized theoretical studies about earth to air heat exchangers and specified them as a numerical model or an analytical model.

Several other papers have been published in which a design method is described. Most of them are based on a descritisation of the one-dimensional heat transfer problem in the tube. Three dimensional complex models, solving conduction and moisture transport in the soil are also found. These methods are of high complexity and often not ready for use by designers. De Paepe and Janssens [40] presented a one-dimensional analytical method to analyze the influence of the design parameters of the heat exchanger on thermo-hydraulic performance. A relation is derived for specific pressure drop, linking thermal effectiveness with pressure drop of the air inside the tube. The relation is used to formulate a design method which can be used to determine the characteristic dimensions of the earth–air heat exchanger in such a way that optimal thermal effectiveness is reached with acceptable pressure loss. The choice of characteristic dimensions becomes thus independent of the soil and climatological conditions. This allows designers to choose the earth–air heat exchanger configuration with the best performance.

Ozgener and Ozgener [41] reported the exergetic performance characteristics of an underground air tunnel system for greenhouse cooling. The data used were obtained from the measurements made in a system, which was designed and installed in the Solar Energy Institute of Ege University, Izmir, Turkey. Ozgener and Ozgener [42] also determined the optimal design of a closed loop EAHE for greenhouse heating by using exergoeconomics. The experimental system studied was installed at the Solar Energy Institute of Ege University, Izmir, Turkey. The results show that the losses in blower and heat exchanger are primarily responsible for exergy destructions in the system. The values of COP and exergy efficiency were found 10.51 and 89.25%, respectively, which were determined to improve the system performance. It is shown in the paper that how the use of simple thermoeconomic optimization methodologies can contribute to find out the accurate design of new equipment.

Ajmi et al. [43] studied the cooling capacity of earth–air heat exchangers for domestic buildings in a desert climate. A sub-soil temperature model adapted for the specific conditions in Kuwait is presented and its output compared with measurements in two locations. Simulation results showed that the EAHE could provide a reduction of 1700 W in the peak cooling load, with an indoor temperature reduction of 2.8 °C during summer peak hours (middle of July). The EAHE is shown to have the potential for reducing cooling energy demand in a typical house by 30% over

the peak summer season. Woodson et al. [44] presented a case study to examine the ground temperature gradient and performance of EAHE in Burkina Faso. Experiments were conducted at burial depth of 0.5, 1.0 and 1.5 m. It is concluded that about 7.6 °C decrease in outdoor temperature is achieved with 25 m long EAHE buried at depth of 1.5 m using a ventilator of 95 m^3/h capacity and the underground temperature was recorded lowest at the time of the day when the outdoor temperature was highest.

Khalajzadeh et al. [45] carried out thermal performance analysis of ground heat exchanger and evaporative cooler hybrid system in summer conditions of Tehran, Iran. The results show that the hybrid system gives cooling effectiveness more than unity and causes significant reduction in air temperature well below the ambient wet-bulb temperature. The hybrid system is capable to replace the conventional air-conditioner effectively. Pfafferott [46] presented a study about evaluation of earth-to-air heat exchangers with a standardized method to calculate energy efficiency. The author studied about temperature behavior, energy gain, general efficiency and thermal efficiency. Thiers and Peuportier [47] studied about thermal and environmental assessment of a passive building equipped with an earth-to-air heat exchanger in France. On basis of extensive monitoring and simulation work, Hollmuller and Lachal [48] examined the fundamental difference between winter preheating and summer cooling potential of buried pipe systems under Central European climate, from an energetic as well as an economic point of view. Hamada et al. [49] described experiments and analyzed on an improved underground heat exchanger by using a no-dig method for the purpose of the cost reduction of a space heating and cooling system using underground thermal energy. Breesch et al. [50] presented that in office buildings, the use of passive cooling techniques combined with a reduced cooling load may result in a good thermal summer comfort and therefore save cooling energy consumption. This is shown in the low-energy office building SD Worx in Kortrijk (Belgium), in which natural night ventilation and an earth-to-air heat exchanger are applied. They [50] evaluated that passive cooling has an important impact on the thermal summer comfort in the buildings. Furthermore, natural night ventilation appears to be much more effective than an earth-to-air heat exchanger to improve comfort.

Vaz et al. [51] conducted experimental and numerical analysis of an earth–air heat exchanger which is used to reduce consumption of conventional energy for heating and cooling of built environments through the use of thermal energy contained in the soil. Zhao et al. [52] performed a study to investigate the thermal performance of saturated soil around coaxial ground coupled heat exchanger (GCHE). An experimental study of thermal and moisture behaviors of dry and wet soils heated by buried capillary plaits was done by Balghouthi et al. [53]. This study was carried out on a prototype similar to an agricultural tunnel greenhouse. Santamouris et al. [54] investigated the impact of different ground surface boundary conditions on the efficiency of a single and a multiple parallel earth-to-air heat exchanger system. Li et al. [55] presented an experimental study of a ground sink direct cooling system (GSDCS) in cold areas. The experimental set up was constructed and tested in Herbin Institute of Technology, Herbin, China. The experimental results reveal that GSDCS studied has immense prospective of energy saving within a particular region. Rodríguez and Díaz [56] described and analyzed the use of low enthalpy geothermal energy that consists of converting mine galleries in underground heat exchangers. Finally, using the method, the capabilities of a typical system were analyzed and its viability from a technical, economic and environmental point of view was proved.

Maerefat and Haghighi [57] presented a study of introduction of use of solar chimney (SC) together with earth to air heat exchanger (EAHE). The finding shows that the solar chimney can be perfectly used to power the underground cooling system during the daytime, without any need to electricity. Eicker and Vorschulze [58] evaluated the performance of vertical and horizontal geothermal heat exchangers implemented in two office building acclimatization projects at Stuttgart, Germany. The main result of performance analysis is that the ground coupled heat exchangers have good coefficients of performance ranging from 13 to 20 as average annual ratios of cold produced to electricity used. It is important to know the temperature field around the heat-exchange pipelines for efficient conversion and use of geothermal energy.

4. Studies conducted on EAHE systems at the Indian universities

The studies conducted on EAHE systems at the Indian universities is divided in to six categories namely, Design optimization studies of EAHE, Cooling/heating performance studies of EAHE, Thermal performance studies of greenhouse with EAHE, Exergy performance studies of EAHE, Energy conservation potential studies of EAHE and Parametric studies of EAHE using artificial neural network (ANN).

4.1. Design optimization studies of EAHE

Genetic algorithms (GAs) have emerged as powerful optimization tool for analyzing the natural problem like earth-to-air heat exchanger (EAHE) and subsequently thermal performance of non air-conditioned building. Advancement in genetic algorithm (GA) optimization tools for design applications, coupled with techniques of soft computing, have led to new possibilities in the way computers interact with the optimization process. The concept of goal-oriented GA has been used by Kumar et al. [59] to design a tool for evaluating and optimizing various aspects of earth-to-air heat exchanger behavior. The developed algorithm is suitable for the calculation of the outlet air temperature and therefore of the heating and cooling potential of the earth-to-air heat exchanger system. This methodology is applicable to a wide range of design optimization problems like choice of building such as green house, solar house, or heating and cooling of buildings by mechanical system.

They [59] presented an intelligent design tool to optimize input variables of an earth-to-air heat exchanger. To determine heating and cooling potential of an EAHE two models were employed, namely deterministic and intelligent. Intelligent model was found superior to deterministic model. The GA designed model incorporates greater accuracy than the previous models. The proposed model accounts for humidity variations of circulating air, natural thermal stratification of the ground, latent and sensible heat transfer, and ground surface conditions, etc. The results show very good agreement with the experimental data and other model predictions. Impact of four inputs humidity, ambient temperature, ground surface temperature and ground temperature at burial depth on outlet temperature of EAHE was studied through sensitivity analysis. Outlet temperature was significantly affected by ambient air temperature and ground temperature at burial depth. Optimum cooling potential of EAHE at Mathura, India was found to be 38 kW h.

4.2. Cooling/heating performance studies of EAHE

Several researchers have studied the use of the ground as heat source and sink such as Bansal et al. [60]. They evaluated a large earth–air–pipe system meant to provide thermal comfort inside the whole building complex at one of the hospitals in India. Kumar et al.

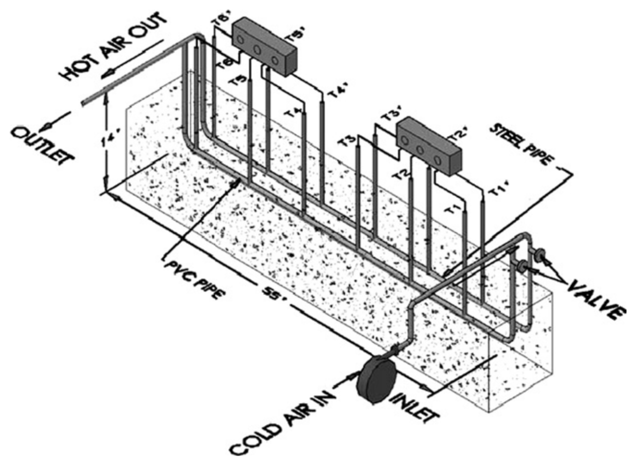


Fig. 3. Experimental set-up of EPAHE (Bansal et al. [1]).

[61] studied heating and cooling potential of an earth-to-air heat exchanger using artificial neural network. The study focuses mostly on those aspects related to the passive heating or cooling performance of the building. Bansal et al. [1] presented that earth–pipe–air heat exchanger (EPAHE) systems can be used to reduce the heating load of buildings in winter. A transient and implicit model based on computational fluid dynamics is developed to predict the thermal performance and heating capacity of earth–air–pipe heat exchanger systems. The model is developed inside the FLUENT simulation program. The model developed is validated against experimental investigations on an experimental set-up in Ajmer (Western India). The experimental set-up of EPAHE is shown in Fig. 3.

For the pipe of 23.42 m length and 0.15 m diameter, temperature rise of 4.1–4.8 °C has been observed for the flow velocity ranging from 2 to 5 m/s. The hourly heat gain through the system is found to be in the range of 423.36–846.72 kW h. In Figs. 4 and 5, points T_{inlet} and T_{exit} represent the inlet and outlet of the buried pipe of the earth–pipe–air heat exchanger system, respectively. Fig. 4 represents the comparison of the results of the simulation and experiments for air velocity of 2.0 m/s at the outlet of the steel and PVC pipes, respectively. Figs. 4 and 5 also depict that as the velocity of air is increased, the temperature of the air at the outlet of the pipe gets reduced. The reduction in temperature of the air at the exit of pipe due to increment in air velocity occurs because when the air velocity is increased from 2.0 to 5.0 m/s, the convective heat transfer coefficient is increased by 2.3 times, while the duration to which the air remains in contact with the ground is reduced by a factor of 2.5. Thus the later effect is dominant and therefore, lesser rise in temperature is obtained at higher air velocities. At higher velocities though the rise in temperature of air is less yet the total heating effect achieved per unit time is much more. It can be seen that the maximum rise in the temperature occurs at air velocity 2 m/s for both PVC and steel pipe. Investigations on steel and PVC pipes have shown that performance of the EPAHE system is not significantly affected by the material of the buried pipe as shown in Fig. 5. Velocity of air through the pipe is found to greatly affect the performance of EPAHE systems. Bansal et al. [2] studied that (EPAHE) systems can also be used to reduce the cooling load of buildings in summer. Effects of the operating parameters (i.e., the pipe material, air velocity) on the thermal performance of earth–air–pipe heat exchanger systems were studied. The 23.42 m long EPAHE system discussed in this paper gives cooling in the range of 8.0–12.7 °C for the flow velocities of 2–5 m/s. Bansal et al. [62] studied that the performance of simple earth–air–tunnel heat exchanger (EATHE) is enhanced by integrating an evaporative cooler at the outlet.

Bansal et al. [63] developed a new concept of 'Derating Factor' for assessment of thermal performance of EAHE under transient

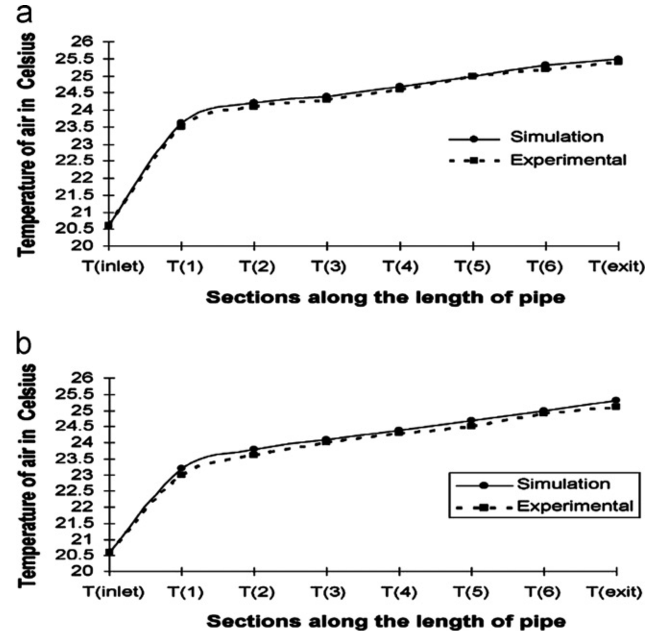


Fig. 4. Temperature distribution along the length of the pipe for exit velocity 2.0 m/s for (a) steel pipe and (b) PVC pipe.

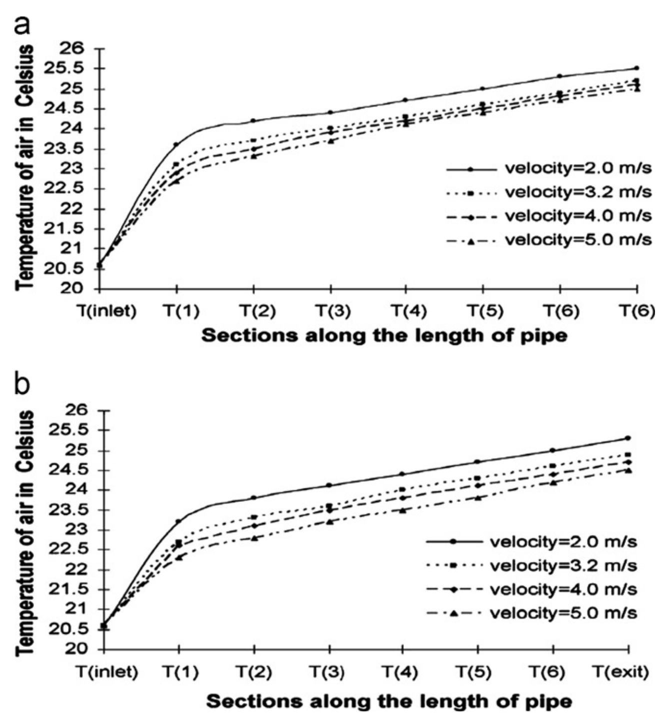


Fig. 5. Simulated temperatures along the length of the pipe for various exit velocities for (a) steel pipe and (b) PVC pipe.

operating conditions. The 'Derating Factor' is defined as the ratio of the difference between the drop in air temperature obtained by EAHE in steady state and in transient state to the drop in air temperature obtained by EAHE in steady state. It is concluded that under transient conditions, thermal performance of EAHE declines due to continuous use of EAHE for long durations. Higher value of 'Derating Factor' indicates greater decline in thermal performance of EAHE. They [63] analyzed different cases and found that the range of derating varies from minimum 0.2% to maximum as 68%, which if ignored while designing may lead to poor performance of EAHEs.

Chel and Tiwari [64] developed a thermal model of a vault roof building integrated with earth to air heat exchanger (EAHE). The building under consideration is made of brick vault and adobe (or mud) structures. Experimental results showed that the room air temperature during winter was found 5–15 °C higher as compared to ambient air temperature while lower during summer months. The results show that annual energy saving potential of the building before and after integration of EAHE were 4946 kW h/year and 10,321 kW h/year, respectively. This considerable increase in annual energy saving potential of building due to EAHE leads to mitigation of CO_2 emissions about 16 t/year and the corresponding annual carbon credit of building was estimated as € 340/year. The life cycle cost (LCC) analysis shows that the payback period is less than 2 years for the investment on EAHE system. Chel and Tiwari [65] realized space heating and cooling with an EAHE integrated stand alone photovoltaic system in New Delhi, India. The authors measured annual performance evaluation and showed energy payback. The total average COP in the experimental period is found to be 10.09.

4.3. Thermal performance studies of greenhouse with EAHE

Ghosal and Tiwari [67] and Ghosal et al. [66] reported the modeling of an earth to air heat exchanger with a greenhouse. Ghosal et al. developed a simplified analytical model to study year around effectiveness of an EAHE coupled greenhouse located in New Delhi, India. They found the temperature of greenhouse air on average 6–7 °C more in winter and 3–4 °C less in summer than the same greenhouse when operating without EAHE [64]. Ghosal and Tiwari developed a new thermal model for green-house heating and cooling with EAHE in New Delhi, India. It was found on average 7–8 °C higher in the winter and 5–6 °C lower in the summer than those of the same greenhouse without EAHE. They showed that greenhouse air temperature increased in the winter and decreased in the summer with increasing pipe length, decreasing pipe diameter, decreasing mass flow rate of flowing air inside buried pipe and increasing depth of ground up to 4 m [66].

Tiwari et al. [68] validated the thermal model given by Ghoshal and Tiwari by round-the-year experimental work at IIT Delhi, New Delhi, India. The correlation coefficient and root-mean-square percentage deviation have been computed for each month for validation of the thermal model. The values are 0.99 and 4.24% for the greenhouse temperature with an earth–air heat exchanger (EAHE) in the month of January. Statistical analysis shows that there is fair agreement between predicted and experimental values. The maximum value of heating potential (11.55 MJ) and cooling potential (18.87 MJ) has been found during off sunshine hours (8 pm–8 am) and peak sunshine hours (8 am–8 pm), for a typical day in the month of January and June.

Nayak and Tiwari [69] carried out a study to evaluate the annual thermal and exergy performance of a photovoltaic/thermal (PV/T) and earth–air heat exchanger (EAHE) system, integrated with a greenhouse, located at IIT Delhi, India, for different climatic conditions of Srinagar, Mumbai, Jodhpur, New Delhi and Bangalore. A comparison is made of various energy metrics, such as energy payback time (EPBT), electricity production factor (EPF) and life cycle conversion efficiency (LCCE) of the system by considering four weather conditions (a–d types) for five climatic zones. The four type of weather conditions for New Delhi have been described as

'a' type, i.e., clear day (blue sky): if diffuse radiation is less than or equal to 25% of global radiation and sunshine hour is more than or equal to 9 h.

'b' type, i.e., hazy day (fully): if diffuse radiation is less than 50% or more than 25% of global radiation and sunshine hour is between 7 and 9 h.

'c' type, i.e., hazy and cloudy (partially): if diffuse radiation is less than 75% or more than 50% of global radiation and sunshine hour is between 5 and 7 h.

'd' type, i.e., cloudy day (fully): if diffuse radiation is more than 75% of global radiation and sunshine hour is less than 5 h.

Ghosal et al. [70] investigated the potential of using the stored thermal energy of ground for space heating with the help of two buried pipe systems, i.e., ground air collector and earth–air heat exchanger, integrated with the greenhouse located in the premises of Indian Institute of Technology, Delhi, India. The total length of the buried pipes in both the arrangements was kept same for making a comparative study. Temperatures of greenhouse air with ground air collector were observed to be 2–3 °C higher than those with earth–air heat exchanger. The temperature fluctuations of greenhouse air were also less when operated with ground air collector as compared to earth–air heat exchanger. Predicted and computed values of greenhouse air temperatures in both the systems exhibited fair agreement. Finally ground air collector was chosen as a suitable option for heating of greenhouse in the above climate.

Shukla et al. [71] developed a thermal model for heating of greenhouse by using different combinations of inner thermal curtain, an earth–air heat exchanger, and geothermal heating.

4.4. Exergy performance studies of EAHE

Nayak and Tiwari [72] carried out theoretical performance assessment of an integrated photovoltaic and earth–air heat exchanger greenhouse using energy and exergy analysis methods. A simplified mathematical model was developed to study round the year effectiveness of photovoltaic/thermal (PV/T) and earth–air heat exchanger (EAHE) integrated with a greenhouse, located at IIT Delhi, India. The solar energy application through photovoltaic system and earth–air heat exchanger (EAHE) for heating and cooling of a greenhouse is studied with the help of this simplified mathematical model. They [72] compared greenhouse air temperatures when it is operated with photovoltaic/thermal system (PV/T) during daytime which is coupled with earth–air heat exchanger (EAHE) at night, with air temperatures when it is operated exclusively with photovoltaic/thermal system (PV/T) and earth–air heat exchanger (EAHE), for 24 h. The results reveal that air temperature inside the greenhouse can be increased by around 7–8 °C during winter season, when the system is operated with (PV/T) system, coupled with EAHE at night.

The isometric view of experimental greenhouse integrated with photovoltaic system and earth–air heat exchanger is shown in Fig. 6. Specification of PV panel, greenhouse and earth–air heat exchanger used for photovoltaic and earth–air heat exchanger coupled greenhouse were given in Table 1. From the results, it is seen that the hourly useful thermal energy generated, during daytime and night, when the system is operated with photovoltaic (PV/T) coupled with earth–air heat exchanger (EAHE) is 33 and 24.5 MJ, respectively. The yearly thermal energy generated by the system has been calculated to be 24,728.8 kW h, while the net electrical energy savings for the year is 805.9 kW h and the annual thermal exergy energy generated is 1006.2 kW h.

4.5. Energy conservation potential studies of EAHE

Kumar et al. [73] presented a numerical model to predict energy conservation potential of earth–air heat exchanger system and passive thermal performance of building has been developed. This model improves upon previous studies by incorporating effects of ground temperature gradient, surface conditions, moisture content and various design aspects of earth–air–tunnel (EAT). The model is based on simultaneously coupled heat and mass transfer in the EAT and is developed within the scope of numerical techniques of finite

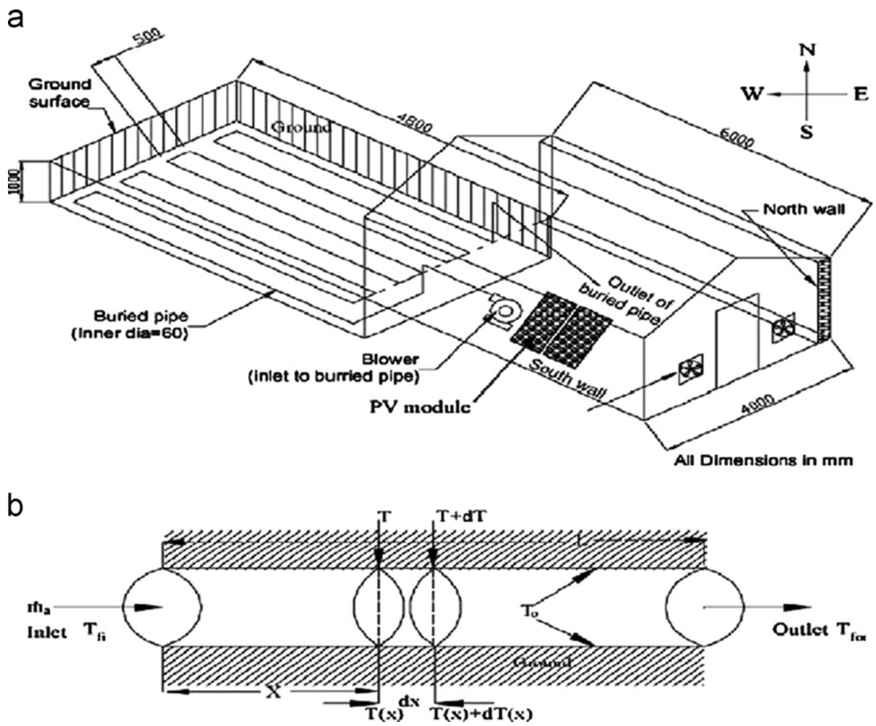


Fig. 6. (a) Isometric view of even span greenhouse integrated with photovoltaic and earth–air heat exchanger arrangement (Nayak and Tiwari [72]). (b) Energy exchange between ground and flowing air in elementary segment of the buried pipe.

Table 1
Main characteristics and technical specifications of the system.

Element	Technical specification
Earth–air heat exchanger	EAHE in serpentine manner (closed loop) with 8 no. of turns, PVC pipes, length of buried pipes: 39 m, buried pipe diameter: 60 mm, distance between two turns: 500 mm, buried depth: 1 m
Blower	0.2 hp capacity
Greenhouse	Even span type greenhouse oriented from east to west direction, Floor Area: 24 m^2
PV Panel	Peak power: 1200 WP, Battery capacity: 14 kW h, No. of PV modules: 16, Area of PV module: 0.61 m^2, Panel dimension: 1.62 × 6.5 m, dc battery: 12 V and 120 Ah, Fan: 12 W
Inverter	2.1 kV A

difference and FFT (MatLab). The model is validated against experimental data of a similar tunnel in Mathura (India), and is then used to predict the tube-extracted temperature for various parameters such as humidity variations of circulating air, air flow rate and ambient air temperature. The model is found to be more accurate in predicting the tube extracted temperature variations along the length (error range ±1.6%). These results are further used to study the thermal performance of a non-air-conditioned building. Cooling potential of 80 m earth tunnel is found adequate (19 kW) to maintain an average room temperature of 27.65 °C. However, auxiliary energy load of 1.5 kW for winter season is required in achieving comfort conditions with EAT system affecting an average room temperature of 24.48 °C. The present model can be easily coupled to different greenhouse and building simulation codes.

4.6. Parametric studies of EAHE using artificial neural network (ANN)

Kumar et al. [74] studied heating and cooling potential of an earth-to-air heat exchanger using artificial neural network. The present study focuses mostly on those aspects related to the passive heating or cooling performance of the building. Two models have been developed for this purpose, namely deterministic and intelligent. The Intelligent model predicts earth-to-air heat exchanger outlet air temperature with an accuracy of ±2.6%, whereas, the deterministic model shows an accuracy of ±5.3%.

5. Conclusions

At a depth of about 1.5 to 2 m the temperature of ground remains almost constant. This constant temperature is called earth's undisturbed temperature. The earth's undisturbed temperature remains always higher than that of ambient air temperature in winter and vice versa in summer. To utilize efficiently the heat capacity of earth EAHE system is to be designed. The outlet of EAHEs can be connected to conventional air-conditioning unit, if cooling or heating achieved is not sufficient. The use of green and clean energy in order to minimize CFC emissions and to minimize conventional energy consumption is in prime focus everywhere. The EAHE systems can play a vital role in minimizing energy consumption by preheating air for heating of different types of buildings in winter and vice versa in summer.

Therefore, design optimization, modeling and testing of EAHE systems is very essential. In the literature several calculation models are found to simulate the thermo-physical behavior of earth–air heat exchangers. A well designed EAHE can reduce electricity consumption of a typical house by 30%.

EAHE systems offer reductions in heating/cooling load of buildings, power consumption, CFC and HCFC consumption and greenhouse gas emissions, and have been extensively used for years. Commonly, the thermal performance of EAHE system increases with increase in length and depth of burial of pipe while the decline in performance is observed with increase in pipe diameter and air velocity.

United States and Europe are world leaders in the use of EAHE systems. The hybrid systems of EAHE and renewable energy sources like solar and wind energy can further improve performance of EAHE system. It may be concluded that efficient use of EAHE systems in combination with sustainable energy sources and latest technology will play an important role in saving energy consumption and environment not only in India but at world level. In this view, it is anticipated by authors that this review paper will be very useful to researchers and scientists working in the field of passive heating/cooling of buildings mainly with the use of EAHE systems.

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